ARMY RESEARCH LABORATORY

An NPSS Model of a Proposed Altitude Test Facility

by Brian C. Huffman, Thomas M. Lavelle, and Albert K. Owen

ARL-RP-310 **February 2011**

A reprint from the *49th AIAA Aerospace Sciences Meeting* Orlando, FL, 4 January 2011.

prepared by

Motile Robotics Inc.
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and

NASA Glenn Research Center
21000 Brookpark Rd.
Cleveland, OH 44135

under contract

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An altitude test facility was modeled using Numerical Propulsion System Simulation (NPSS). This altitude test facility model was developed to explore the capabilities of NPSS for modeling this type of thermodynamic system. A new building in construction for the US Army Research Laboratory's Vehicle Technology Directorate will contain an altitude test facility. With the aid of the NPSS developers at NASA, the facility of the same type was modeled using the NPSS software. The model allows for developing control algorithms, variations in component performance and parametric studies of the effects of different configurations. This simulation development provides the capability to model testing facilities from an aerothermodynamics perspective. A parametric study measured component performance in various configurations. Development of a simulation to accurately model the facility to be built will be developed when the facility design is finalized.

Nomenclature

ft	=	feet
hp	=	horse power
Lbm	=	pound mass
MSL	=	mean sea level
RPM	=	revolutions per minute
s	=	seconds
shp	=	shaft horse power

I. Introduction

BY September 30, 2011, the US Army Research Lab's Vehicle Technology Directorate will be moved from its current locations at NASA Langley Research Center and NASA Glenn Research Center to the US Army's Aberdeen Proving Grounds (APG) as a part of the Department of Defense's recurring efforts to consolidate and reduce cost[1].

As a part of this move, a number of new test facilities will be constructed at APG. One of these will be a "small" altitude test facility capable of testing 200 shp engines at altitudes up to 25,000 ft. The contract to design and build this facility was signed in May of 2010, so some information such as: performance, a simplified schematic, and the size of the facility is currently available.

The development of a performance model for an altitude test facility is advantageous for several reasons. First, it allows for the development of control algorithms for the facility. Variations of component performances can be easily explored. The effects of different configurations can be studied to help guide the design process. However, no performance model exists. This required the development of a highly flexible "notional" altitude test facility model that can be rapidly and easily changed to accommodate new ideas and perform parametric studies.

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To implement this model, the Numerical Propulsion System Simulation (NPSS) environment was selected. This software, widely used in the aero-propulsion industry, was first developed to model gas turbine aircraft engines. However, its extreme flexibility has allowed it to be used in modeling a wide variety of thermodynamic systems. Recently, for example, a closed cycle Brayton system for space power applications was modeled[2]. This application provided several modules used in the altitude test facility model.

II. The Numerical Propulsion System Simulation

The NPSS environment is based on object oriented programming principles[3, 4]. While models developed within this architecture are able to represent any system, its primary function thus far has been in the development of performance models, largely for gas turbine engines.

All simulations are created from a collection of five basic types (classes) of building blocks, which represent engine components, and describe how components are linked together. These classes are elements, subelements, flow stations, ports, and tables. Elements are primary building blocks connected together by ports. They perform high level calculations. An example of an element would be a compressor or turbine block. Subelements are interchangeable secondary building blocks that are a part of elements or other subelements. An example of a subelement would be an instrument specific compressor map calculation. Flow stations are responsible for thermodynamic and continuity calculations. Ports provide linkages between the elements. There are five types of ports: mechanical, fluid, fuel, data, and thermal. Tables are used to calculate heat transfer equations and to access flow station properties.

These objects can be assembled into system models that can realistically represent engineering systems of varying complexity. The computer code used within NPSS is very similar to C++ code. The objects used can either be part of the standard library package or can be custom elements developed outside of the main NPSS package. While a number of papers provide a more general overview of the system, a paper by Binder[5] provides an excellent comprehensive discussion of the environment and its capabilities.

The NPSS system is currently being used extensively in industry. Both General Electric (GE) and Pratt and Whitney (PW) are using the environment to support the simulation requirements of their new engine programs. The software is extremely flexible and can support all aspects of development program from conceptual design to transient performance modeling, engine test analysis, and data reduction. In addition, having a common tool between the companies has made teaming between companies on new engine projects much easier. For example, the GP7200 engine (a joint GE/PW effort to power the new Airbus A380 airplane), the F135 (PW engine for the Joint Strike Fighter), and F136 (GE/Rolls Royce engine for the JSF) engines are current joint programs using the NPSS environment.

In addition to the increased fidelity that is possible, the companies have found advantages in the flexibility of the software. It is easy for the companies to implement their own algorithms at their specific locations. All that is required to create a new engineering element is to create a file which defines its ports, variables, and calculating function (description of its engineering processes). Since NPSS fully supports interpreted elements, it is not necessary to compile the new elements. The elements can just be read right in with the input file. In fact, all of the NPSS standard elements are released in both a compiled and interpreted form. The compiled form allows for speed. The interpreted form allows for easy customization.

III. Module Development

The NPSS software contains a wide variety of gas turbine engine and rocket engine components, such as compressors, turbines, and pumps. A recently developed model of a closed cycle dual Brayton model required the development of a more representative duct, heat exchanger, and heater modules[2]. Several of the modules developed for the basic package and others from the Brayton package were used in the development of the altitude test facility model presented here.

Most of the model can be created using existing NPSS elements. Nonetheless several new elements were required. First, a simple liquid/gas heat exchanger was created to model the cooling effect of the air flow. In addition, an altitude chamber element was created to model the effects of inserting an engine inside the physical confines of a chamber. This element was derived from a previous NPSS element, an engine bypass. The duct element was modified to model the heat loss to the outside world to determine the external temperature of the physical pipes. Finally, a joiner element was created to combine flow from two sources into one flow. It was derived from the standard splitter element which performs just the opposite function.

IV. The Model

Figure 1 is a screen shot from the NPSS Graphical User Interface (GUI) of the model that is discussed in this paper. This model is similar to a proposed Army facility. However, the model contains many of the components and features that will occur in the facility at APG. For example, the model is capable of altitude and ground operation. It will be able to provide a broad range of flows and temperatures to the test chamber. The heat exchangers in the model can be made to operate on a variety of cooling fluids. The user would just need to supply the thermodynamics of the cooling fluid in tabular form.

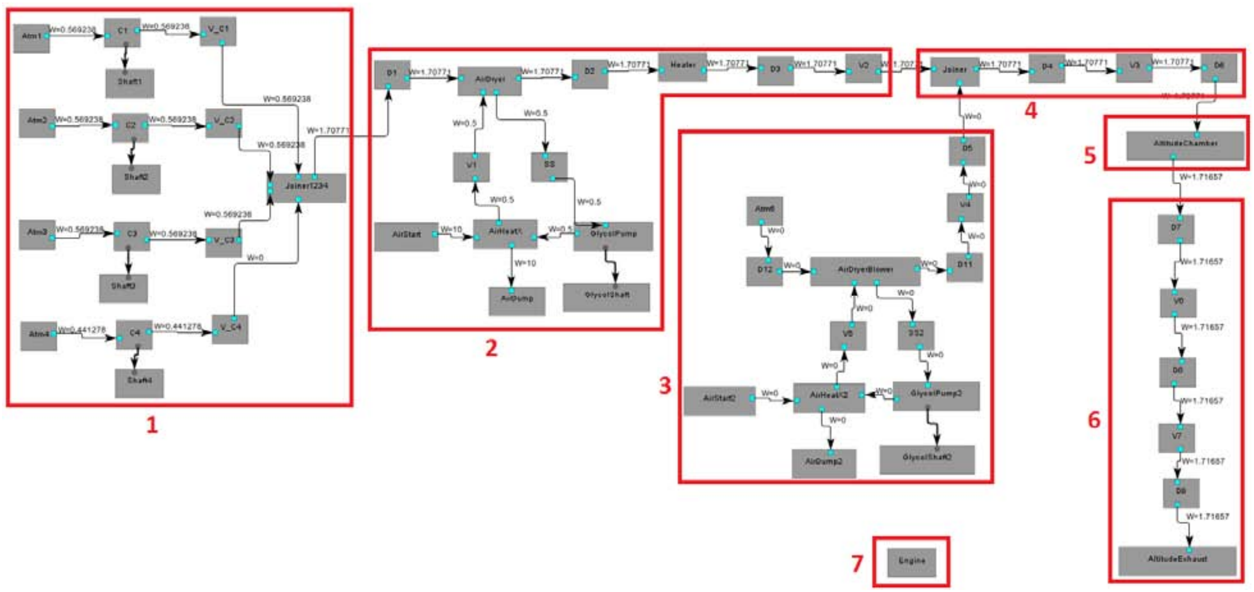


Figure 1. Altitude Test Facility NPSS Model GUI. C=Compressor, V=Valve, D=Duct, Atm=Atmospheric Flow Start, SS=Start Stop Flow

Region 1) Atmospheric flow start elements with the same properties are linked to four compressors linked in parallel for altitude operations. Each compressor has a shaft to provide its power. The compressors each connect to a regulation valve. All of the mass airflows are combined within the joiner element where they are ducted to Region 2.
Region 2) Temperature conditioning equipment. The current model uses water as the cooling fluid in the heat exchangers. The airflow moves through ducts, air dryer element, and valves as it move to Region 4. The air dryer element is connected to pumps and heat exchangers to adjust air temperature.
Region 3) This configuration is used for ground testing. It consists of atmospheric air ducted to a heat exchanger to adjust air temperature and ducted to the joiner in Region 4.
Region 4) Upstream ducting. The joiner can switch between the two possible sources of mass airflow depending on what test conditions are desired.
Region 5) Altitude chamber element. This could equivalently be considered the wind tunnel test section. The engine element from Region 7 is physically located within the altitude chamber for all calculations.
Region 6) Exhaust valves and ducting to atmosphere. These represent the physical exhaust ducting valves required to vent the airflow exiting the altitude chamber.
Region 7) Test article, in this case a small 50 shp turboshaft engine. It is linked in parallel with the test chamber. The chamber is modeled in a manner similar to a fan bypass. The air is split into bypass and non-bypass flows by the specification of the bypass ratio. Thus the incoming airflow is set so that the engine receives the required airflow for its operating condition.

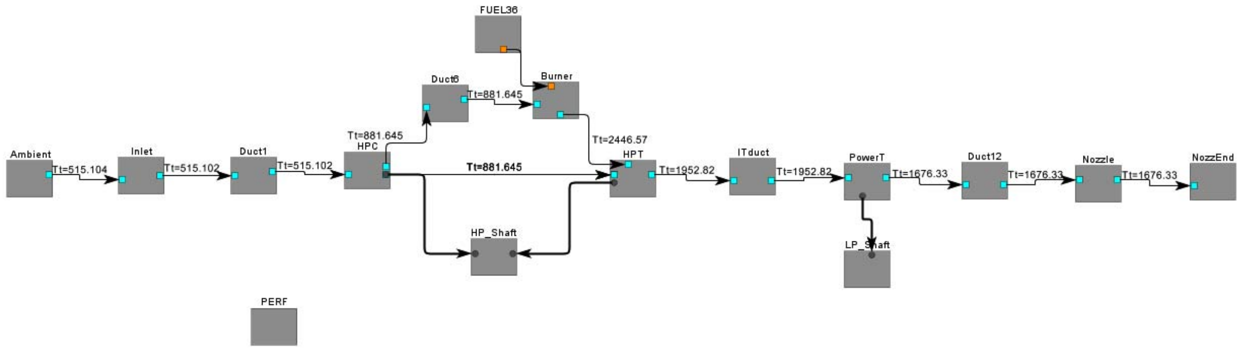


Figure 2. NPSS Model of a 50 shp Turboshaft Engine. HPC=High Pressure Compressor, HPT=High Pressure Turbine

Figure 2 shows the turboshaft engine model GUI configuration of the test article used for these parametric studies. This refers to Region 7 in Figure 1. The model is executed by specifying the engine operating conditions (speed, power output, bypass ratio) and the altitude chamber conditions (chamber pressure, temperature). It will return all performance parameters throughout the system. Different engines, modeled similarly to this one, can be linked in parallel to the altitude chamber where they can be operated and the facility operating requirements for those engines can be determined.

The current engine model remains under development. The next component to be added will be a two-dimensional mixing model downstream of the engine exhaust to improve the accuracy of the mixing losses occurring in this area.

V. Model Operation

The model can be operated from either the command line or from the GUI. Operation from the command line allows relatively easy observation to the convergence of the model and, perhaps more importantly, creates an output file that can contain the performance parameters that are of interest to the researcher. Operation using the GUI allows a broader awareness of the entire system operation since any desired parameter, such as total temperature or mass airflow, can be displayed above the “wire” links between any or all components in the model.

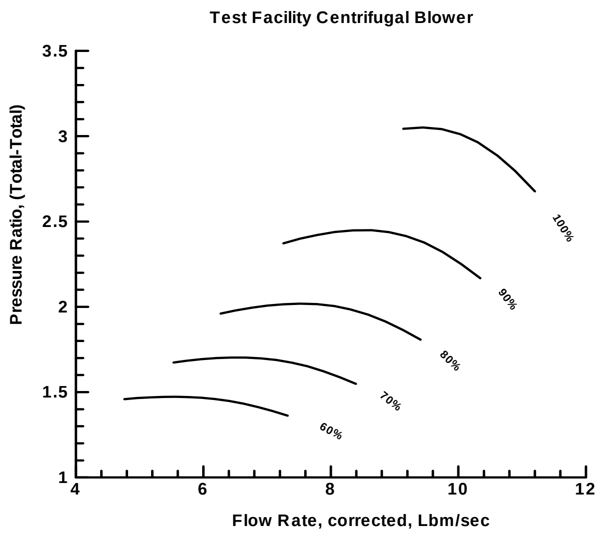
To vary the operating conditions of the model, the model file of the facility is opened. Any text editor, such as notepad, may be used, although the GUI provides a powerful and convenient editor. Any independent parameter can be varied but the parameters used for controlling this model are: engine speed and power, altitude chamber altitude and temperature, the number of facility compressors operating, and the engine bypass ratio (BPR). The BPR, combined with the altitude chamber cross sectional area, allow for the calculation of airspeed in the chamber. In addition, outside air conditions can be specified for system operation at non standard conditions.

The model can be run either in the design mode or the off design mode. In the design mode, the facility compressor maps will be modified to reflect a specific operating design point (efficiency, mass flow, and pressure ratio). Operation in this mode enables parametric studies of different compressor designs. Normally, operation will be in the off design mode where all components are fixed.

During the convergence process, the model solver balances the operation of both the engine and the facility. This means that, for the facility, the compressors move on their performance maps along with the heat exchangers and other facility components to provide a converged solution. The time required to do this is only a few seconds.

VI. Results

To demonstrate the capabilities of the facility simulation, several parametric studies were completed. For the following parametric studies, the facility was configured with four continuous flow compressors. The test engine was a 50 shp notional turboshaft engine. The performance charts of the notional compressors for the facility were provided by Mr. Joseph Veres of the Glenn Research Center while Mr. Chris Snyder, also of Glenn Research Center, provided the notional 50 shp gas turbine engine model. (Figure 2)



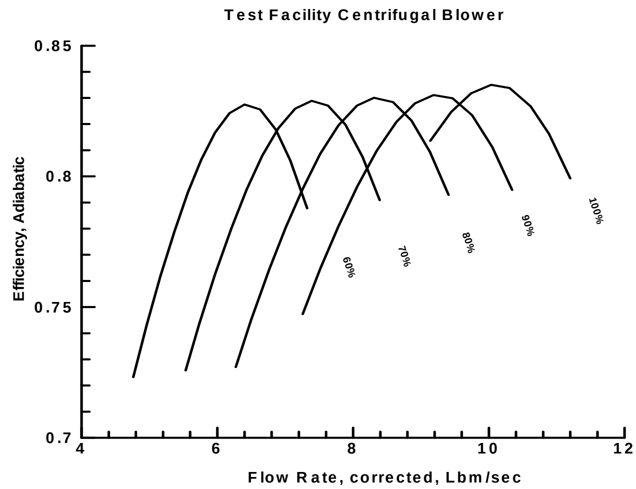
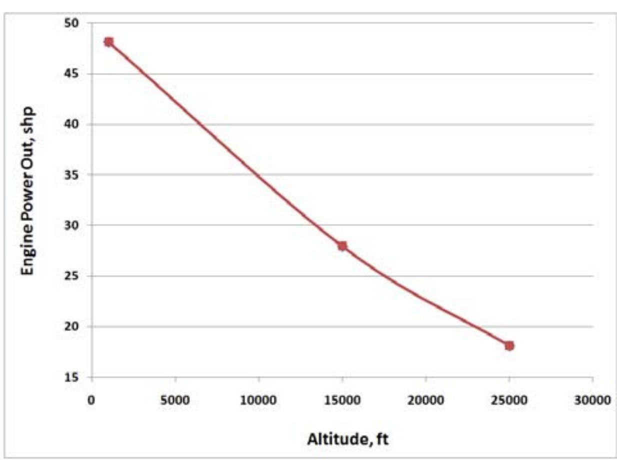


Figure 3. Facility Compressor Pressure Ratio vs Mass Flow.

Figure 4. Facility Compressor Efficiency vs Mass Flow.

Figure 3 provides the facility compressor pressure ratio map and Figure 4 is the compressor facility efficiency plot. This compressor design is characterized by a relatively broad operating range at all speeds and, more importantly, a relatively gradual drop off in efficiency as mass flow rises. There is no choking flow shown in the maps provided. In Figure 4, the peak efficiencies at all given speeds are near 83%. They gradually decrease as speed is reduced. The model software modified the compressor efficiency maps during its design phase to reflect a 92% efficient compressor at a pressure ratio of 3. This was done to demonstrate the design capability of the model.

The study operated the facility over a range of altitudes and airflows for a gas turbine engine operating at full power. Total altitude chamber airflow variation was from a factor of five to a factor of twice the total engine airflow. Chamber altitude was set to 1,000 ft MSL, 15,000 ft MSL, and 25,000 ft MSL. The facility was operated in two configurations using either three or four compressors.



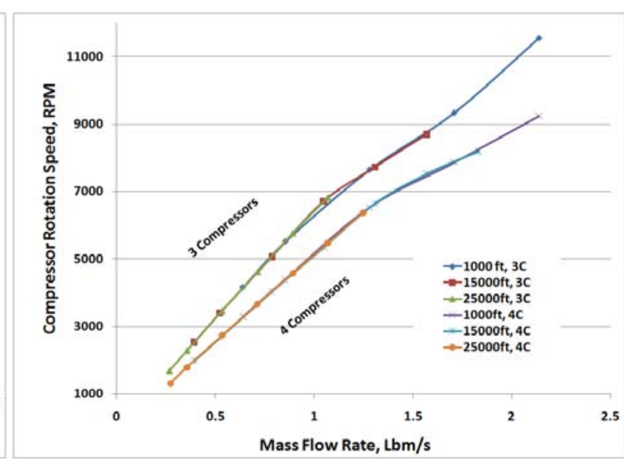


Figure 5. Engine Power Output vs. Altitude.

Figure 6. Compressor Speed vs. Mass Flow.

Figure 5 shows the notional engine power output. During the study, the engine was operated at 100 % speed. As can be seen from Figure 5, power developed decreases by almost 2/3 as the altitude was increased from 1,000 feet above sea level to 25,000 feet MSL, as would be expected due to the decreasing air density as altitude increases. Engine RPM also decreased by approximately 700 RPM as the engine altitude was increased. For this integrated engine/facility model both components (engine and facility) are solved simultaneously.

Figure 6 shows the required facility compressor speed as a function of chamber required mass flow. As would be expected, the higher the required mass flow, the higher the required compressor speed. The significant difference in speeds between the operation with three facility compressors and four facility compressors reflects the large variation of airflows required at different altitudes and chamber airspeeds. There is only one operating line for each individual study case (three or four compressors), because the inlet conditions for these compressors always remains the same, standard day atmospheric. The BPR was set at: 0.5, 1, 2, 3, 4, and 5 resulting in the increased mass flowrates.

The current model does not incorporate structural limitations. As a result, the model does not indicate the limiting compressor speed. The design point for the facility compressors used for this model was 8,000 RPM, so for the purposes of this example, the limiting compressor speed was set to 9,000 RPM. Figure 6 shows that this model can be used to determine at what airflow a particular configuration of facility compressors will reach its limiting operating speed.

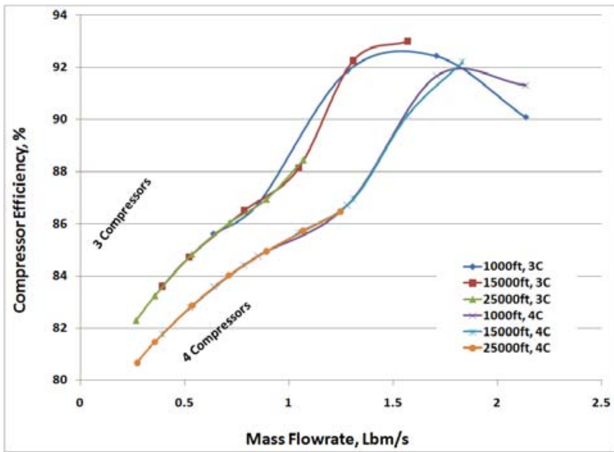


Figure 7. Compressor Efficiency vs. Mass Flow.

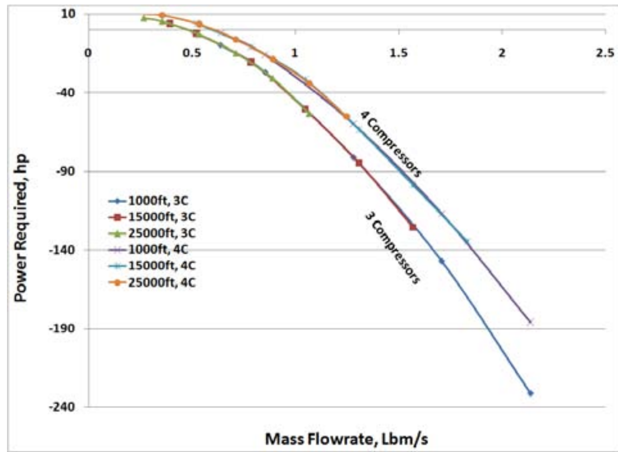


Figure 8. Power Required by Facility vs. Compressor Mass Flow.

Figure 7 shows the facility compressor efficiency lines for operation using three and four compressors. Notice that the aerodynamic efficiency is higher during operation with three compressors than with four compressors over most of the mass flow range where both can successfully operate. At very high mass flows compressor efficiencies drop off and operation with four compressors becomes more efficient. The system downstream appears to be better matched for operation with four compressors than three, resulting in higher losses between the compressor exit and the chamber inlet than when operating with four compressors.

Figure 8 reflects the compressor power required. Since power is consumed by the compressors, the more negative the number, the more power required. Figure 8 also indicates a positive power and power production at low flows. The positive number indicates that the compressors are operating as turbines and providing power due to the low pressure downstream and the minimal required massflow. This is an unrealistic operating condition in the facility and indicates that the facility must change the number of compressors operating during testing at these conditions. However, the power required over most of the operating range is lower with four compressors than with three compressors. It would seem that this is the result of the total system design.

As the required airflow increases, the operating point moves up the compressor operating line and eventually reaches the design point at 8,000 RPM. Figure 6 shows that this occurs at roughly 1.4 Lbm/s when operating with three facility compressors and roughly 1.75 Lbm/s with four operating compressors. The unusual curves in Figure 7 are likely a result of the selection of points used for the study and the plotting routine used to plot the results. Additional points would likely have resulted in the two efficiency plots: one plot for three compressors and one plot for four compressors, collapsing to only two lines. One final note is that facility operation with four compressors results in lowering the operating speed over the range of airflows considered to below 8,000 RPM, the design speed. Thus, the compressors never need to operate beyond the design point where operation gives lower efficiencies.

VII. Conclusion

An integrated system of an engine performance model and an altitude facility performance model was created within the NPSS environment. This model represents the first public application of the NPSS modeling environment to such a facility. This model allows easy modification of altitude chamber parameters such as air pressure, temperature, and velocity. The model also allows easy modification of the engine operation, such as power output or engine RPM, within the model. The customization of elements allows further development.

Such a simulation allows rapid parametric studies of various facility configurations, compressor resizing, and power losses. For example, should power required be a significant issue, the model can be used to accomplish trade studies to specify the number and performance of compressors used in the facility. It can provide information showing when the configuration of the facility should be changed during the course of a proposed test plan for a specific engine in the facility. The customization of elements allow for more precise data or a broader range of measurements to be performed. Should there be particular operating conditions that the facility should not be operated at; the model can alert planners of any given test if these would prove to be a problem.

Perhaps most importantly, the model will allow studies of facility control logic. Thus, when coupled to a control simulation program, designers can develop control logic for a proposed test facility. This shows the remarkable flexibility and broad potential applicability of the NPSS environment.

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